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Strength and Hydraulic Conductivity Characteristics of Sand-Bentonite Mixtures Designed As a Landfill Liner

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ABSTRACT

Compacted sandy soils with addition of bentonite have been used in a variety of geotechnical structures as engineered barriers, such as in landfill liners and hydraulic containment structures. In this study, Igbokoda sand was mixed with bentonite at varying percentages of 0%, 2%, 4%, 6%, 8% and 10% by weight of sand. Strength tests, which include compaction test, California Bearing Ratio (CBR) test and direct shear test, were performed on various sand-bentonite mixtures using standard methods. Hydraulic conductivity tests were also performed on various sand-bentonite mixtures in order to determine their suitability as landfill liner. Results from the tests showed that 8% of bentonite with sand mixture had a hydraulic conductivity below 1×10^{-7} cm/s, a cohesion value of 250 kN/m^3 and a reasonable strength (CBR) value of 54.07% using the West Africa standard compactive method, hence being the safest of the selected varying percentages for the design of a landfill liner.

KEYWORDS: Bentonite, California Bearing Ratio (CBR), Compacted landfill liner, Hydraulic conductivity, Igbokoda sand.

INTRODUCTION

Waste containment systems, such as landfills, and hydraulic containment systems, such as reservoirs, are required to have appropriate liners in order to prevent the passage of leachate into the soil and groundwater environment. To effectively carry out this function, compacted soil liners are designed to have low hydraulic conductivity, k, which in many cases is considered to be less than 1×10^{-7} cm/s (Shackelford et al., 2000; Osinubi and Amadi, 2009; Osinubi et al., 2009; Shackelford and Sample-Lord, 2014). In order to attain the values of hydraulic conductivity specified by international regulations ($k < 1 \times 10^{-7}$ cm/s), addition of bentonite to local soils is a commonly adopted method (Francisca and Glatstein, 2010). Sand-bentonite mixture could therefore meet the hydraulic conductivity requirement without suffering from shrinkage cracking. The sand component decreases the shrinkage on drying and below a limiting clay content, sand particles are in contact, providing mechanical stability and preventing shrinkage. When wet, clay fills the sand voids, providing a low hydraulic conductivity for the mixture. To minimize cost and avoid shrinkage cracking, it is important that the amount of clay added to a mixture is kept close to the minimum required to meet the hydraulic conductivity specifications. Permeameter tests using distilled water indicate that mixtures containing more than 5% bentonite by dry weight achieved the required value, although it may be much higher when a landfill leachate is used as permeant (Wu and Khera, 1990).

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Bentonite, a pure mineral clay consisting mostly of montmorillonite, has proven to be effective in enhancing the membrane property of clay, by which landfill liners can have better barrier performance towards the migration of contaminants (Qiang et al., 2015). Bentonite is widely used in the industry for bonding, plasticizing and suspending applications. However, the properties of bentonite that make it useful as a landfill liner with sand are its large specific surface area, high swelling potential and low hydraulic conductivity to water (Gleason et al., 1997). Apart from being a low permeability barrier, bentonite is also effective as clay liner, because it has a high swelling capacity, which reduces the amount required (Taha and Taha, 2015). Researchers have studied the influence of initial compaction conditions, pore solution and suction on swelling behaivour of sand-bentonite mixture (Qin et al., 2008; Baille et al., 2010). Chen et al. (2015) conducted a series of oedometer tests on bentonite/sand mixtures to investigate compression and swelling behaviours. They concluded that the swelling deformation of bentonite/sand mixture has three phases. In the first phase, swelling strain increases rapidly, then gradually decreases and stabilizes in the final phase. Mishra et al. (2010) performed an experimental study on fifteen different soil-bentonite mixtures to understand their physical, chemical and mineralogical compositions and found that bentonite's physical and mineralogical properties considerably influence the hydraulic and consolidation properties of sand-bentonite mixtures. Bello (2011) conducted compaction and unconfined compression tests on radish brown tropic soils to study the range of water content and dry unit weight at which compacted test specimens would have adequate shear strength and observed that unconfined compressive strength values should be $\leq$ 200 kN/m^2, which is the minimum acceptable value for materials to be used as hydraulic barriers in containment structures.

Landfill liner can be prepared by using locally available soil if it satisfies certain conditions, the most important condition being a low hydraulic conductivity of less than 1×10^{-7} cm/s. The primary design can be done such that the resultant mix should have a minimum of 20%-30% fines and the percentage gravel should not exceed 30% (Datta and Juneja, 1997; Jones et al., 1995). The maximum particle size is restricted to 25-50 mm. The liquid limit of the material should be at least 20% and plasticity index between 12% and 30%. This design can be adopted once it is found that the mix has a minimum shear strength of 200 kPa and a maximum volumetric shrinkage of 4% upon drying (Bello and Adegoke, 2013). Hydraulic barriers (also known as liners) used for waste containment structures in landfill design play a vital role in impeding fluid flow and attenuating inorganic contaminants. The structural integrity of these hydraulic barriers must be ensured by making sure that the constructed facility has adequate shear strength. According to Osinubi and Bello (2009), the material should have adequate shear strength (a minimum unconfined compressive strength of 200 kN/m^2) and be durable to withstand destructive forces of alternating wet/dry and freeze/thaw cycles. This strength is the lowest value for very stiff soils based on the consistency classification (Osinubi and Bello, 2009).

The objective of this study was to determine the most suitable sand-bentonite mixture that yields acceptable hydraulic conductivity and strength required in the construction of waste landfill liners using sandy soil treated with low-percent bentonite. Low bentonite was used in order to achieve an appropriate degree of impermeability without undermining strength integrity or inducing excessive desiccation shrinkage and low compressibility in mixtures associated with bentonite treatment.

MATERIALS AND METHODS

Materials

Sand: The sand used in this study was taken from Igbokoda located in the southern part of Ondo State. The area lies within the geographical coordinates of latitude 06.34°N and longitude 04.79°E. Sand samples were collected in Igbokoda town, along Igokoda-Ayetoro Road in Ilaje Local Government Area. The tools used for the collection of samples for the purpose of this project were shovel, hand auger, sample bag/sack and measuring tape. The soil samples were collected using shovel and kept in sample bags. The samples were collected at the proximity of Ofara river. The region is covered by three to eight meters overburden sand with dense clay underneath. The soil is a finely grained sand that contains little pebbles, ash-like in colour, smooth to touch and less coarse. Igbokoda silica sand has been established as a reference standard sand for engineering research work in Nigeria, since it has geotechnical and mineralogical characteristics closest to the standard Ottawa sand and needs little processing to bring it to the same level as standard baseline sand, like the Ottawa sand (Ojuri and Fijabi, 2012).

Bentonite: Bentonite in powdered form used in this study was a representative of the typical bentonite available for construction purposes.

Methods

The Igbokoda sand sample was air dried after sampling. For samples containing bentonite, the relevant quantities of dry soil and bentonite (0, 2, 4, 6, 8 and 10% by weight of soil) were mixed. The index properties of the soil and soil mixtures were measured with a weighing balance in accordance with standard procedures outlined in BS 1377 (1990) and Head (1994a). Strength tests, which include direct shear test and California Bearing Ratio (CBR) test, were conducted in accordance to procedures outlined in BS 1377 (1990). For compaction test, samples were compacted using two methods; i.e., British Standard Light (BSL) and West African Standard (WAS), to simulate the range of compaction energies expected in the field. The BSL compaction procedures are described in BS 1377 (1990) and Head (1994a). The West African Standard (WAS) compaction, which is in accordance with the Nigerian General Specifications (1997), is the conventional energy level commonly used in the West African region. Hydraulic conductivity was measured using a compaction mould permeameter under falling head condition, as recommended by Head (1994b). Processed soil samples were directly compacted into the compaction mould with the two energies at predetermined moulding water contents. Each specimen was soaked for at least 48 h in tap water before the commencement of permeation. The permeant liquid was tap water and hydraulic conductivity test was terminated after a steady flow was established; i.e., when there was no statistically significant trend in hydraulic conductivity over time (Jo et al., 2005).

RESULTS AND DISCUSSION

Preliminary Tests on Sand Sample

The particle size distribution curves of the natural Igbokoda sand sample presented in Figure 1 show that the percents passing sieve number 200 and sieve number 40 are 1.58% and 90.48%, respectively and that the corresponding coefficient of uniformity (C_u) and coefficient of curvature (C_c) are 1.8 and 1.1, respectively. The fine content of the sand is found to be non-plastic. The index properties of the soil showed that the moisture content of the sand was 4.82% and specific gravity was 2.64.

Preliminary Tests on Bentonite

Result of a sieve analysis showed that 84% of the air dry material passed BS No. 200 sieve. The properties as well as the oxide composition of bentonite are reported in Table 1. The liquid limit was 228%, while the plastic limit was 88%. The plasticity index (PI) of bentonite, which was 140%, indicates that it is highly plastic and has a high swelling potential. The natural moisture content and specific gravity of the bentonite sample were 15.25% and 2.31, respectively. The chemical composition of the bentonite sample showed that the main oxides were silicon and aluminium oxides with a percentage composition of 58.14% and 21.73%, respectively.

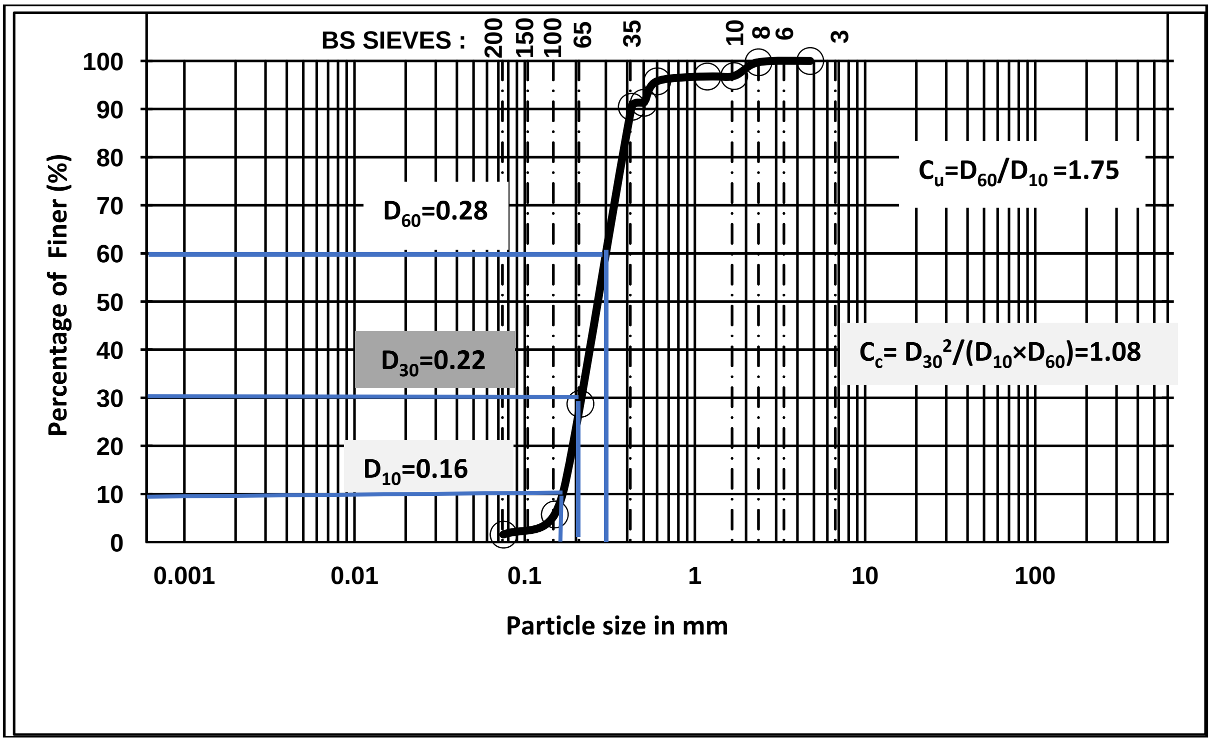

Figure (1): Particle size distribution curve of tested soil

Table 1. Properties and oxide composition of bentonite

Property	Value	Oxide	Percentage (%)
Liquid limit (%)	228	CaO	0.86
Plastic limit (%)	88	SiO_2	58.14
Plasticity index (%)	140	Al_2O_3	21.73
Linear shrinkage (%)	11.43	Fe_2O_3	2.46
Moisture content (%)	15.25	MgO	2.42
Percent passing sieve no. 200 (%)	84	TiO_2	1.86
Specific gravity	2.31	Na_2O	2.08
Swelling potential	High	Loss on ignition	13.28

Compaction Characteristics

The variations of maximum dry density (MDD) and optimum moisture content (OMC) with bentonite content for various mixtures are shown in Figure 2 and Figure 3, respectively. The compactive effort had a great influence on the landfill liner as reported by Osinubi and Moses (2015) and as evident in Figures 2 and 3. It is clear from Figure 2 that as the bentonite content increased, the MDD increased slightly for both compactive efforts. For British Standard Light (BSL) compactive effort, as the bentonite content increased from 0% to 10%, MDD increased from 16.05 kN/m^3 to 17.75 kN/m^3. For West African Standard (WAS) compactive effort, as the bentonite content increased from 0% to 10%, MDD increased from 16.02 kN/m^3 to 17.70 kN/m^3. The behavior of MDD is mostly based on the addition of bentonite, while the type of compaction has little effect on the MDD values.

Figure 3 shows that as the bentonite content increased, the OMC decreased slightly at first and increased later on for both compactive efforts. For British Standard Light (BSL) compactive effort, OMC decreased from 13.6% at 0% bentonite to 11.8% at 2% bentonite and increased later on to 15.2% at 10% bentonite. For West African Standard (WAS) compactive effort, OMC decreased from 15.8% at 0% bentonite to 12.3% at 4% bentonite and increased later on to 15.9% at 10% bentonite.

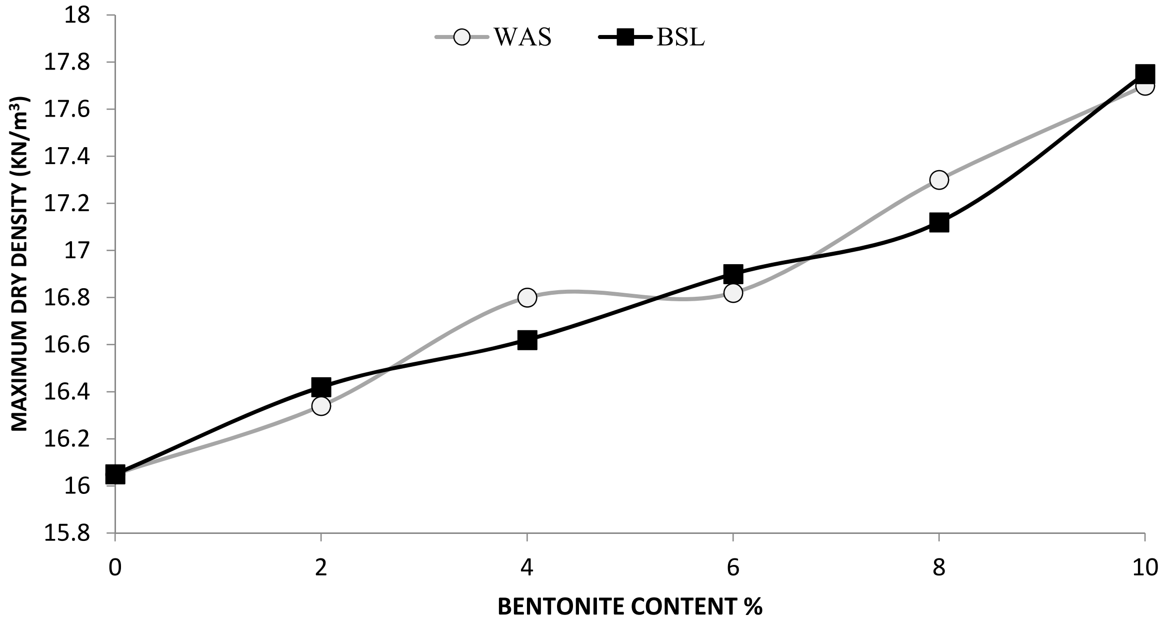

Figure (2): Variation of maximum dry density (MDD) with bentonite content

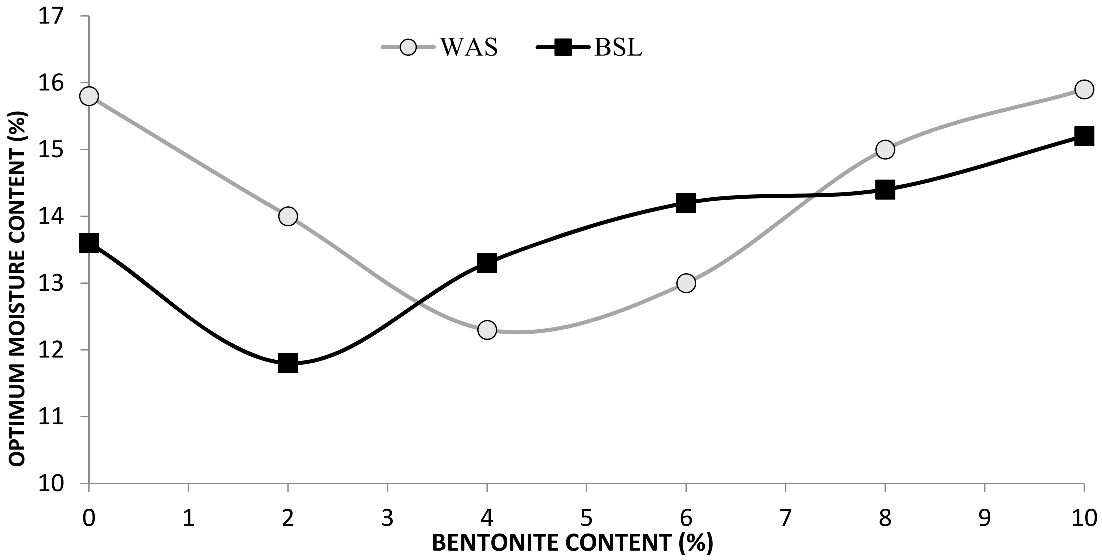

Figure (3): Variation of optimum moisture content (OMC) with bentonite content

California Bearing Ratio (CBR)

The variations of bearing ratio with bentonite content for various mixtures are shown in Figure 4. It is clear from Figure 4 that as the bentonite content increased, the bearing strength increased for both compactive efforts. For British Standard Light (BSL) compactive effort, as the bentonite content increased from 0% to 10%, the bearing ratio increased from 7.01% to 29.64%. For West African Standard (WAS) compactive effort, as the bentonite content increased from 0% to 10%, the bearing ratio increased from 11.85% to 92.51%. The behavior of the bearing ratio of sand is not only affected by the addition of bentonite, but also by the type of compaction, as the bearing ratio is much higher with the West African Standard (WAS) compactive effort than that with the British Standard Light (BSL) compactive effort.

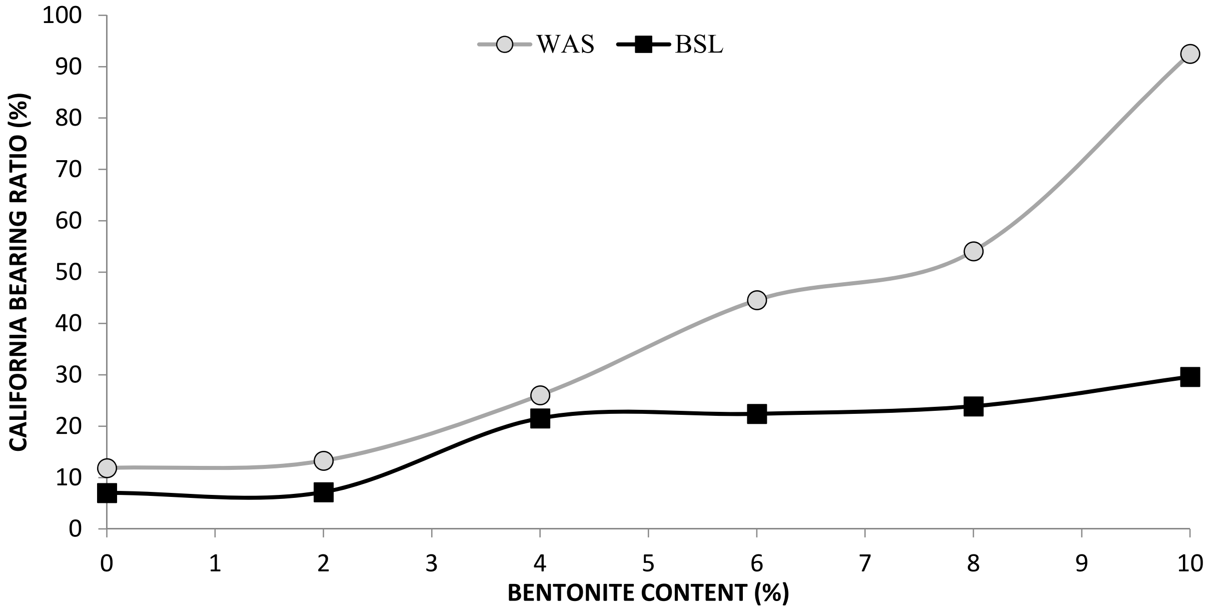

Figure (4): Variation of California bearing ratio with bentonite content

Direct Shear Test

The variations of the angle of internal friction and the cohesion obtained from the direct shear test with bentonite content for various mixtures are shown in Figure 5. The figure shows that as the bentonite content increased from 0% to 8%, the angle of internal friction decreased from 38° to 20° and increased later on to 24° when the bentonite content was 10%. Cohesion increased from 0 to 250 kN/m^2 as the bentonite content increased from 0% to 8%. The cohesion value decreased to 220 kN/m^2 when the bentonite content was 10%.

Hydraulic Conductivity Test

The effects of bentonite content and compaction energy on the hydraulic conductivity (k) of various sand-bentonite mixtures are reported in Figure 6. From the figure, a decrease in hydraulic conductivity was achieved with higher bentonite content and a relatively small amount of bentonite was needed to achieve the acceptable hydraulic conductivity (Amadi and Osinubi, 2010; Amadi et al., 2011). As the bentonite content increased from 0% to 10%, the hydraulic conductivity decreased from 3.97 $\times 10^{-5}$ cm/s to 5.62 $\times 10^{-9}$ cm/s for the British Standard Light (BSL) compaction energy and from 3.11×10^{-5} cm/s to 7.89×10^{-9} cm/s for the West African Standard (WAS) compaction energy. The hydraulic conductivities of mixtures with less than 6% bentonite are greater than 1×10^{-7} cm/s, while mixtures with 6% bentonite and more have hydraulic conductivities less than 1×10^{-7} cm/s. The common regulatory requirement for compacted soil liners states

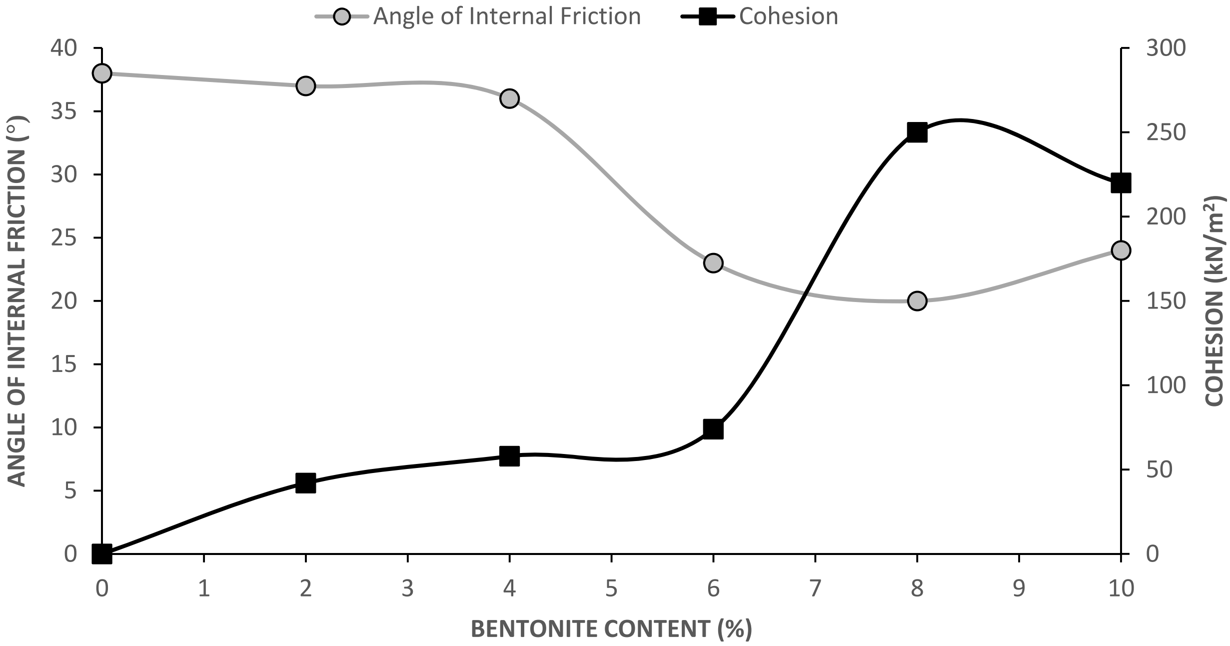

Figure (5): Variation of angle of internal friction and cohesion from the direct shear test with bentonite content

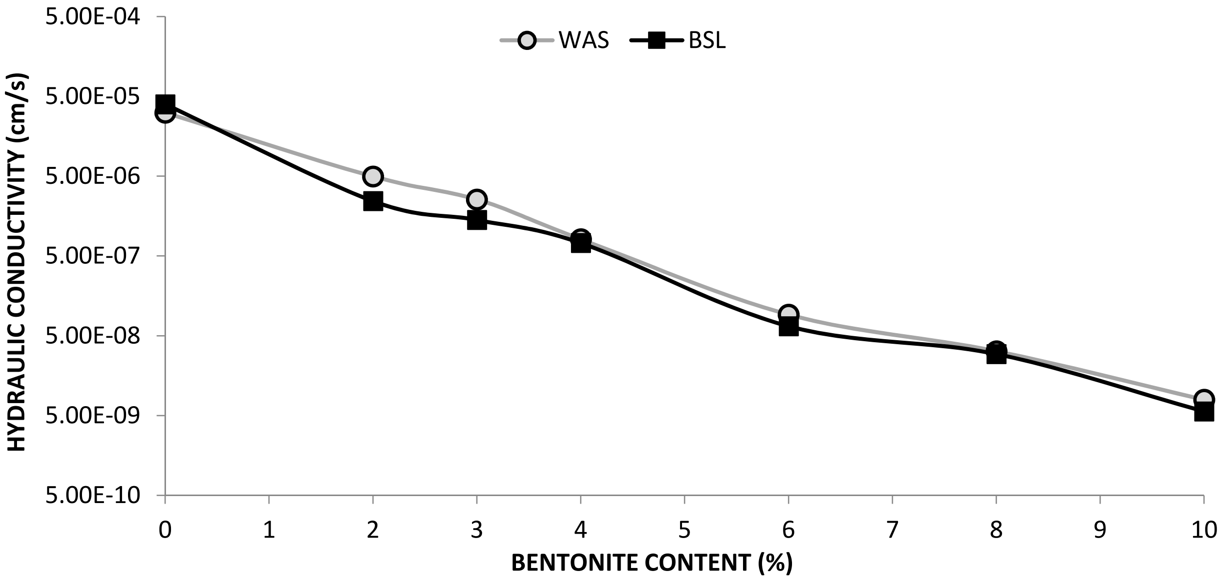

Figure (6): Variation of hydraulic conductivity with bentonite content

that hydraulic conductivity should be less than 1×10^{-7} cm/s. Thus, the compacted sand-bentonite mixtures with 6% bentonite or more are adequate to be used as liners. The high specific surface of bentonite and fine bentonite particles which resulted in adsorption of a large number of hydrated cations as well as water molecules contributed to the decrease of hydraulic conductivity in soil–bentonite mixtures. Similar results have been reported in Morandini and Leite (2015) and in Mukherjee and Mishra (2015) for other soils treated with bentonite.

CONCLUSIONS

In successfully building a safe compacted soil liner, specific requirements, such as low hydraulic conductivity and high bearing strength values, must be met during construction. In this study, bentonite was added to sandy soil to achieve these specified requirements. From the test results, the following conclusions can be deduced:

- 8% of bentonite content with sand was the safest, most effective and most economical mix in this study, because it achieved a hydraulic conductivity of 3.2×10^{-8} cm/s which is less than 1×10^{-7} cm/s.
- 8% of bentonite content with sand also showed a reasonable structural integrity, where CBR values were 23.89% and 54.07% at BSL and WAS compaction energies, respectively, while cohesion and angle of internal friction obtained from the direct shear test were 250kN/m^3 and 20°, respectively.
- It was observed that bentonite addition was not solely responsible for the changes in hydraulic conductivity and strength values. Compaction energy also had an effect on hydraulic conductivity and strength values.

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